# Attachment: Delivery Documentation for the Aura Ground Star Catalogs

This memorandum documents the analysis and quality assurance completed to produce the recently generated Aura ground star catalogs. In addition, the report provides mission specific information about the content of the ground catalogs and detailed descriptions of the ground catalog quality flags. It also includes comparisons of the contents of the ground and onboard Aura catalogs, as well as comparisons of each of these catalogs to a body of charge-coupled device star tracker (CCDST) data gathered by the star tracker onboard the Submillimeter Wave Astronomical Satellite (SWAS).

## GROUND STAR CATALOG CHARACTERISTICS

The ground star catalogs for the Aura mission were generated using the SKYMAP System (an input Master Star Catalog and the mission star catalog generation program MMSCAT). The Master Catalog (MC) used was Version 5 of the SKY2000 Master Catalog. The resulting SKYMAP run catalog contains 25,677 entries with a predicted limiting instrumental magnitude of +7.25. Positions and proper motions are on the International Celestial Reference System (ICRS) at epoch 2000. The selected standard star for the Aura CCDST photometric system was G0V. The radius within which near-neighboring stars were combined into single ground catalog entries was 180 arcseconds. A blended run catalog entry (containing two or more individual stars) includes a blended predicted instrumental magnitude and the position of the brightest component (in the Aura photometric system). The run catalog produced is an all-sky catalog and has no limiting magnitude on the brighter end. Also delivered for use by Aura is a specialized run catalog where SKYMAP identifiers have been replaced by identification numbers from the TRW onboard star catalog (OBC) for all run catalog stars that are also in the OBC. This catalog contains 25,678 entries, as one OBC star (SKYMAP 10070077/OBC 2420, see the section of this memo comparing the two catalogs) has a SKYMAP-predicted instrumental magnitude fainter than the limiting run catalog magnitude of +7.25. A third run catalog delivered is the SKYMAP run catalog OBC subset, containing the 3,542 OBC stars, each with run catalog data fields and an OBC number in place of a SKYMAP identifier.

## SKYMAP RUN CATALOG FORMAT AND QUALITY FLAG DEFINITIONS

Each Aura SKYMAP run catalog entry (see Table A-1 for the format of an entry) contains eight hexadecimal quality flags used to assist in determining the suitability of a given star as a potential guide star for attitude determination. Individual quality flags and the bin values selected during the generation of the Aura run catalog are described in this section.

## Table A-1. SKYMAP Run Catalog Record Format

<table>
<tr><th>Name</th><th>Type</th><th>Description</th></tr>
<tr><td>ISTDAT</td><td>I*4</td><td>SKYMAP number</td></tr>
<tr><td>FSTDAT(1)</td><td>R*4</td><td>X-component of GCI unit vector</td></tr>
<tr><td>FSTDAT(2)</td><td>R*4</td><td>Y-component of GCI unit vector</td></tr>
<tr><td>FSTDAT(3)</td><td>R*4</td><td>Z-component of GCI unit vector</td></tr>
<tr><td>FSTDAT(4)</td><td>R*4</td><td>Visual (V) or instrumental magnitude</td></tr>
<tr><td>FSTDAT(5)</td><td>R*4</td><td>Composite word (proper motion word):<br><br>Integer part—Direction of star’s total proper motion vector divided by 360.0, multiplied by 1000, and rounded to the nearest integer<br><br>Fractional part—Magnitude of star’s proper motion vector in arcseconds per year divided by 100</td></tr>
<tr><td>FSTDAT(6)</td><td>R*4</td><td>Composite word (quality flag word): Contains eight 4-bit flags used to quantify the quality of a star as a potential guide star; each flag measures the quality of a different physical aspect and includes the following:<br><br>
<table>
<tr><th>Bits</th><th>Description</th></tr>
<tr><td>1-4</td><td>Variability</td></tr>
<tr><td>5-8</td><td>Color</td></tr>
<tr><td>9-12</td><td>Multiplicity</td></tr>
<tr><td>13-16</td><td>Near-neighbors</td></tr>
<tr><td>17-20</td><td>Position knowledge error</td></tr>
<tr><td>21-24</td><td>Magnitude knowledge error</td></tr>
<tr><td>25-28</td><td>Trackability near-neighbor (spare)</td></tr>
<tr><td>29-32</td><td>Identifiability near-neighbor (spare)</td></tr>
</table>
</td></tr>
<tr><td>FSTDAT(7)</td><td>R*4</td><td>Composite word (color word):<br><br>Integer part—(B-V) color multiplied by 100 and rounded to the nearest integer; = 999 if no (B-V) color is available<br><br>Fractional part—SKYMAP-coded spectral type divided by 100000</td></tr>
</table>

The first quality flag is the variability flag. It maps a star's variability amplitude in magnitudes as described in Table A-2. In general, this variability amplitude is not the amplitude of variability in the sensor passband of a particular CCDST. Rather, it is the observed variability in a particular astronomical passband (e.g., Johnson *V*). However, this amplitude can be used to obtain a rough idea of the degree of variability of a particular star.

**Table A-2. Run Catalog Quality Flag 1 Definition (Variability)**

| Flag Value | Definition |
|---|---|
| 0 | 0.0 = amplitude < 0.1 |
| 1 | 0.1 = amplitude < 0.2 |
| 2 | 0.2 = amplitude < 0.3 |
| 3 | 0.3 = amplitude < 0.4 |
| 4 | 0.4 = amplitude < 0.5 |
| 5 | 0.5 = amplitude < 0.75 |
| 6 | 0.75 = amplitude < 1.0 |
| 7 | 1.0 = amplitude < 2.0 |
| 8 | 2.0 = amplitude < 3.0 |
| 9 | 3.0 = amplitude < 4.0 |
| 10 | 4.0 = amplitude < 5.0 |
| 11 | 5.0 = amplitude < 6.0 |
| 12 | 6.0 = amplitude < 8.0 |
| 13 | 8.0 = amplitude < 10.0 |
| 14 | Amplitude = 10.0 |
| 15 | Known variable with unknown amplitude |

The second quality flag is the color flag. It maps the difference between the input magnitude on a standard astronomical passband (e.g., Johnson *V*) used to predict the sensor passband magnitude by MMSCAT, and the predicted sensor passband magnitude itself. This difference (in magnitudes) indicates the degree of difference between the input magnitude and the output magnitude prediction. Table A-3 describes the mapping used to assign values to this flag.

**Table A-3. Run Catalog Quality Flag 2 Definition (Color)**

| Flag Value | Definition |
|---|---|
| 0 | -100.0 = color < 0.05 |
| 1 | 0.05 = color < 0.1 |
| 2 | 0.1 = color < 0.2 |
| 3 | 0.2 = color < 0.3 |
| 4 | 0.3 = color < 0.4 |
| 5 | 0.4 = color < 0.5 |
| 6 | 0.5 = color < 0.6 |
| 7 | 0.6 = color < 0.85 |
| 8 | 0.85 = color < 1.0 |
| 9 | 1.0 = color < 1.25 |
| 10 | 1.25 = color < 1.5 |
| 11 | 1.5 = color < 1.75 |
| 12 | 1.75 = color < 2.0 |
| 13 | 2.0 = color < 2.5 |
| 14 | 2.5 = color < 3.0 |
| 15 | Color = 3.0 |

The third quality flag is the multiplicity flag. For stars that are known to be members of double- or multiple-star systems, it maps the magnitude difference (in magnitudes) between the two brightest components. See Table A-4 for a detailed description of the mapping of this quality flag.

**Table A-4. Run Catalog Quality Flag 3 Definition (Multiplicity)**

| Flag Value | Definition |
|---|---|
| 0 | Not a multiple star or multiple star treated as a near-neighbor |
| 1 | Nearest star is either greater than or equal to 6.0 magnitudes fainter, or is less than 0.1 arcseconds away, or if definition of values 0 or 2-7 does not apply |
| 2 | 4.0 = magnitude difference < 6.0 |
| 3 | 3.0 = magnitude difference < 4.0 |
| 4 | 2.0 = magnitude difference < 3.0 |
| 5 | 1.0 = magnitude difference < 2.0 |
| 6 | 0.5 = magnitude difference < 1.0 |
| 7 | Magnitude difference < 0.5 |

The fourth flag is the near-neighbor flag. It maps net position uncertainties of primary stars (in arcseconds) as a result of interfering near-neighbor stars. Despite the fact that pairs or groups of stars closer together than 180 arcseconds have been blended in the Run Catalog, the quality of the position given for the brightest component of the pair or group is expected to be degraded in quality from what would be expected for a solitary star. Quality flag four attempts to model this degradation with an additional position uncertainty mapped in arcseconds. See Table A-5 for a detailed mapping of this quality flag.

**Table A-5. Run Catalog Quality Flag 4 Definition**
**(Near-Neighbor Position Interference)**

| Flag Value | Definition |
|---|---|
| 0 | -1.0 = additional position uncertainty < 0.0 |
| 1 | 0.0 = additional position uncertainty < 1.0 |
| 2 | 1.0 = additional position uncertainty < 2.0 |
| 3 | 2.0 = additional position uncertainty < 3.0 |
| 4 | 3.0 = additional position uncertainty < 4.0 |
| 5 | 4.0 = additional position uncertainty < 5.0 |
| 6 | 5.0 = additional position uncertainty < 6.0 |
| 7 | 6.0 = additional position uncertainty < 8.0 |
| 8 | 8.0 = additional position uncertainty < 10.0 |
| 9 | 10.0 = additional position uncertainty < 30.0 |
| 10 | 30.0 = additional position uncertainty < 50.0 |
| 11 | 50.0 = additional position uncertainty < 100.0 |
| 12 | 100.0 = additional position uncertainty < 200.0 |
| 13 | 200.0 = additional position uncertainty < 500.0 |
| 14 | 500.0 = additional position uncertainty < 1000.0 |
| 15 | additional position uncertainty = 1000.0 |

The fifth flag is the position knowledge uncertainty flag. It maps the RMS position uncertainty (ICRS2000) contained in the MC (in arcseconds). The mapping used to assign values to this flag is described in Table A-6.

**Table A-6. Run Catalog Quality Flag 5 Definition (Position Knowledge)**

| Flag Value | Definition |
|---|---|
| 0 | 0.0 = position measurement uncertainty < 1.0 |
| 1 | 1.0 = position measurement uncertainty < 3.0 |
| 2 | 3.0 = position measurement uncertainty < 5.0 |
| 3 | 5.0 = position measurement uncertainty < 10.0 |
| 4 | 10.0 = position measurement uncertainty < 25.0 |
| 5 | 25.0 = position measurement uncertainty < 75.0 |
| 6 | 75.0 = position measurement uncertainty < 150.0 |
| 7 | 150.0 = position measurement uncertainty < 9999.0 |
| 8 | Position measurement uncertainty = 9999.0 |

The sixth flag is the predicted magnitude knowledge uncertainty flag. It maps the uncertainties associated with predicted sensor passband magnitudes from MMSCAT. This uncertainty includes the initial uncertainty of the input magnitude used by MMSCAT and an estimate of the uncertainties associated with different methods of predicting sensor passband magnitudes used by MMSCAT. Table A-7 details the mapping used to assign values to this flag.

**Table A-7. Run Catalog Quality Flag 6 Definition (Predicted Magnitude)**

| Flag Value | Definition |
|---|---|
| 0 | 0.0 = magnitude error < 0.05 |
| 1 | 0.05 = magnitude error < 0.1 |
| 2 | 0.1 = magnitude error < 0.2 |
| 3 | 0.2 = magnitude error < 0.3 |
| 4 | 0.3 = magnitude error < 0.4 |
| 5 | 0.4 = magnitude error < 0.5 |
| 6 | 0.5 = magnitude error < 0.6 |
| 7 | 0.6 = magnitude error < 0.8 |
| 8 | 0.8 = magnitude error < 1.0 |
| 9 | 1.0 = magnitude error < 1.25 |
| 10 | 1.25 = magnitude error < 1.5 |
| 11 | 1.5 = magnitude error < 1.75 |
| 12 | 1.75 = magnitude error < 2.0 |
| 13 | 2.0 = magnitude error < 2.25 |
| 14 | 2.25 = magnitude error < 2.5 |
| 15 | Magnitude error = 2.5 |

The seventh quality flag is the trackability near-neighbor flag. It maps the angle in degrees to the nearest star either brighter than or up to 4.0 magnitudes fainter than the run catalog star. Nearby stars can interfere with the ability of a star sensor to track a particular star, and this flag serves to indicate the presence of potentially interfering nearby stars. Table A-8 details the mapping used to assign values to this flag.

**Table A-8. Run Catalog Quality Flag 7 Definition (Trackability)**

| Flag Value | Definition |
|---|---|
| 0 | Near-neighbor separation = 1.0 |
| 1 | 0.9 = near-neighbor separation < 1.0 |
| 2 | 0.8 = near-neighbor separation < 0.9 |
| 3 | 0.7 = near-neighbor separation < 0.8 |
| 4 | 0.6 = near-neighbor separation < 0.7 |
| 5 | 0.5 = near-neighbor separation < 0.6 |
| 6 | 0.4 = near-neighbor separation < 0.5 |
| 7 | 0.3 = near-neighbor separation < 0.4 |
| 8 | 0.25 = near-neighbor separation < 0.3 |
| 9 | 0.2 = near-neighbor separation < 0.25 |
| 10 | 0.15 = near-neighbor separation < 0.2 |
| 11 | 0.125 = near-neighbor separation < 0.15 |
| 12 | 0.1 = near-neighbor separation < 0.125 |
| 13 | 0.075 = near-neighbor separation < 0.1 |
| 14 | 0.05 = near-neighbor separation < 0.075 |
| 15 | 0.0 = near-neighbor separation < 0.05 |

The eighth flag is the identifiability near-neighbor flag. It maps the angle in degrees to the nearest star within 1.0 magnitudes of the run catalog star in brightness. A nearby star similar in brightness to a particular run catalog star can be confused with the run catalog star and tracked instead of the intended star. This quality flag serves to help identify potential situations of this sort. Table A-9 details the mapping used to assign values to this flag.

**Table A-9. Run Catalog Quality Flag 8 Definition (Identifiability)**

| Flag Value | Definition |
|---|---|
| 0 | Near-neighbor separation = 5.0 |
| 1 | 4.0 = near-neighbor separation < 5.0 |
| 2 | 3.2 = near-neighbor separation < 4.0 |
| 3 | 2.5 = near-neighbor separation < 3.2 |
| 4 | 2.0 = near-neighbor separation < 2.5 |
| 5 | 1.5 = near-neighbor separation < 2.0 |
| 6 | 1.25 = near-neighbor separation < 1.5 |
| 7 | 1.0 = near-neighbor separation < 1.25 |
| 8 | 0.75 = near-neighbor separation < 1.0 |
| 9 | 0.625 = near-neighbor separation < 0.75 |
| 10 | 0.5 = near-neighbor separation < 0.625 |
| 11 | 0.4 = near-neighbor separation < 0.5 |
| 12 | 0.3 = near-neighbor separation < 0.4 |
| 13 | 0.25 = near-neighbor separation < 0.3 |
| 14 | 0.2 = near-neighbor separation < 0.25 |
| 15 | 0.0 = near-neighbor separation < 0.2 |

## RECOMMENDATIONS FOR CATALOG USE

The run catalog delivered is an all-sky catalog (see Figure A-2). The density of the catalog varies in different regions of the sky, as the only cutoff applied to stars input from the SKY2000 V5 MC was in predicted instrumental magnitude.

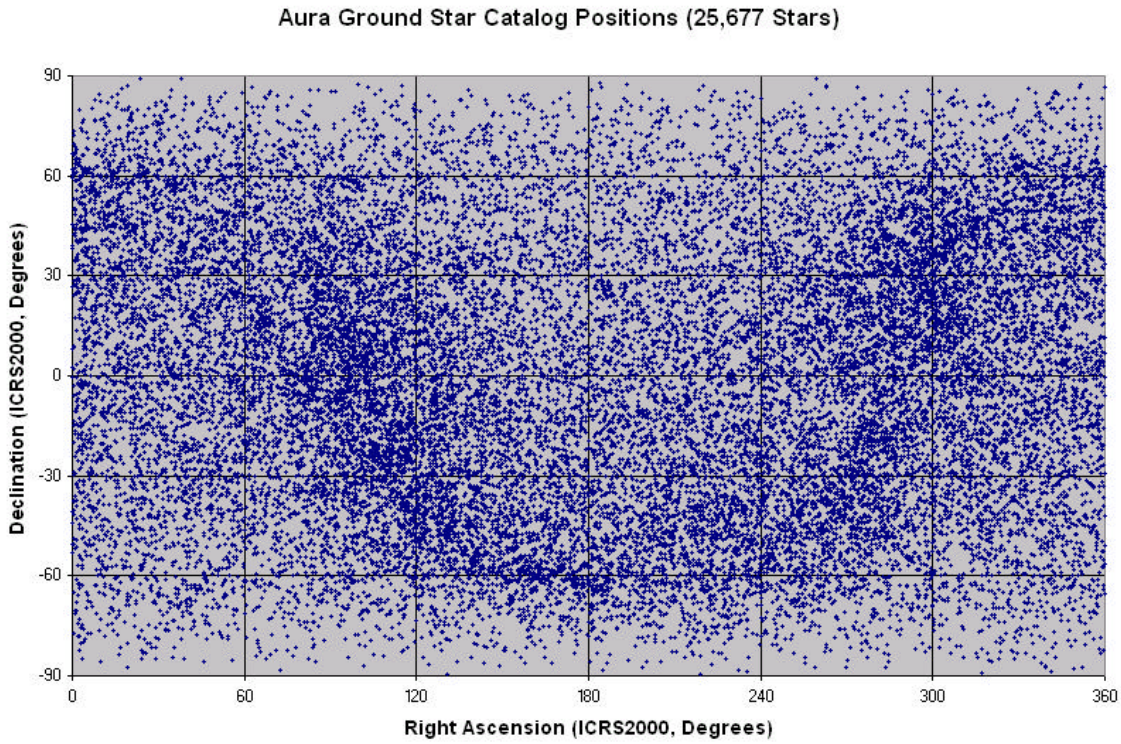


**Figure A-2. Aura Ground Catalog Star Positions**

Variable stars are included in the Aura ground catalogs and can be identified by using quality flag 1 (variability amplitude, see Table A-2) in the run catalog. These stars are not recommended for use as guide stars due to the element of uncertainty involved when attempting to acquire and track them.

Quality flags seven and eight (near-neighbor interference) are based on stars present in the SKY2000 Version 5 MC. Stars not contained in the SKYMAP Master Catalog cannot be accounted for, and some of these stars are known to be bright enough for the Aura CT-602 star trackers to detect.

As a result of the improvements to the content of the SKYMAP MC and to the instrumental magnitude prediction techniques of MMSCAT, a non-variable star with no measurable near-neighbor interference can be expected to produce magnitude residuals (difference of CT-602 measurement and SKYMAP prediction) of less than 0.25 magnitudes. This is expected to be the case for all tracked stars regardless of spectral type/color.

# COMPARISON OF AURA GROUND STAR CATALOG AND AURA ON-BOARD STAR CATALOG

Inasmuch as each catalog is intended to model the same CCDSTs, the Aura ground catalogs can be directly compared to the Aura on-board catalog (OBC). The Aura OBC used in this comparison contained 3,542 stars selected according to brightness in the Aura CCDST passband, distribution on the sky, and qualities such as variability or the presence of detectable near-neighbor stars. The positions given in the Aura OBC appear to be based on the Hipparcos Catalogue (all but one of the OBC stars are in either the Hipparcos Main catalog or the Hipparcos Component catalog). These positions agree to the subarcsecond level with the same stars from the Aura ground catalogs (which also use Hipparcos astrometry for Hipparcos stars). Both the Aura ground catalogs and the OBC contain variable stars, but those included in the OBC are generally of small variability amplitude in standard passbands, or of unknown variability amplitude. The ground catalogs include a variability amplitude quality flag described in a previous section of this memo in each entry to allow the screening of stars by variability. Both the Aura ground catalogs and the OBC contain stars with potentially interfering near-neighbor stars. The OBC generally includes stars with detectable near-neighbors only if the angular separation of the two stars is very small, so that centroid determination of a defocused image in the CCDST is not significantly affected. Stars with near-neighbors at larger angular separations are included in the OBC if the neighboring stars are sufficiently fainter than the primary star as to not have a significant effect on measurement of the primary. The Aura ground catalogs contain several quality flags relating to near-neighbor stars as described in a previous section of this memo. The Aura ground catalogs contain single entries for pairs or groups of stars where two or more stars within a 180-arcsecond radius contribute significantly to the measured image. The single entry includes the position of the brightest component star (in the passband of the Aura CCDST), and a blended magnitude reflecting all nearby stars providing a significant contribution to the measured flux.

In order to form the SKYMAP run catalog with OBC numbers in place of SKYMAP identifiers and also the OBC subset of the run catalog, the OBC and the run catalog were cross-referenced. This allows position and magnitude differences to be computed. Figure A-3 shows the differences in predicted magnitudes (SKYMAP-OBC) for OBC stars that are not known or suspected variable stars. (Two stars, 10070077 and 13370069, have predicted magnitude differences of 3.02 and 2.74, respectively. Both are spectral type M9. SKYMAP 10070077 is not actually in the final SKYMAP run catalog [but is in the run catalogs incorporating OBC i.d.s, see earlier section], as its predicted magnitude of 7.292 is fainter than the ground catalog limiting magnitude.)

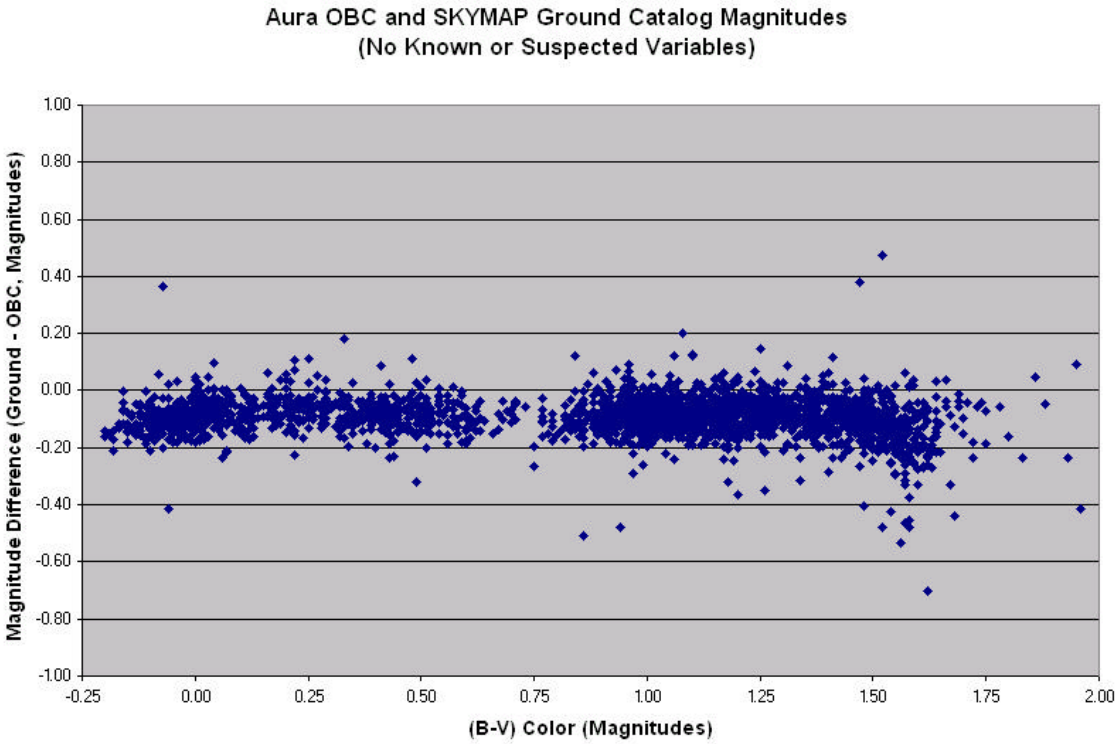


**Figure A-3. Aura OBC and SKYMAP Predicted Magnitude Differences (No Variable Stars)**

## COMPARISON OF MEASURED SWAS MAGNITUDES TO AURA OBC AND SKYMAP PREDICTED MAGNITUDES

In 1998, measured CCDST magnitudes were acquired from the SWAS mission. After analysis and reduction, SWAS CCDST magnitudes converted to the RXTE CCDST photometric system were added to 678 stars in what became the SKY2000 Version 3 Master Catalog. The original SWAS magnitudes were measured by a CT-601 CCDST on a G0V-based photometric system, which makes them very valuable in analyzing predicted Aura CCDST magnitudes, which are for CT-602s on a G0V-based system.

Approximately six hundred of the stars measured by SWAS are in the Aura OBC. After elimination of known or suspected variable stars, and of stars with too few SWAS observations to form a reliable mean magnitude, Figures A-5 and A-6 show magnitude residuals based on SWAS measurements and catalog predictions. Figure A-5 shows the magnitude differences (SWAS-OBC) for the remaining SWAS stars. Figure A-6 shows the same distribution for the SKYMAP ground catalog predicted magnitudes for the same SWAS stars. Many of the outlier points on Figures A-5 and A-6 correspond to the same stars, and in many cases the deviation from expectation appears to be caused by poor quality SWAS mean magnitudes that were not put into the SKYMAP Master Catalog for this very reason.

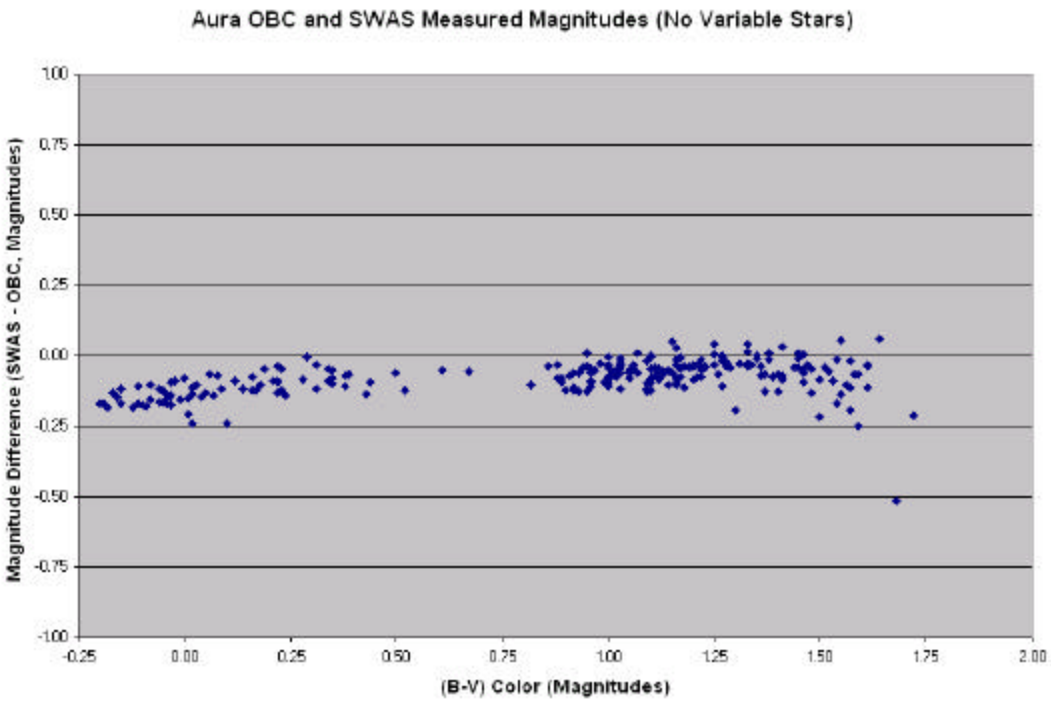


**Figure A-5. Aura OBC and SWAS Measured Magnitudes**

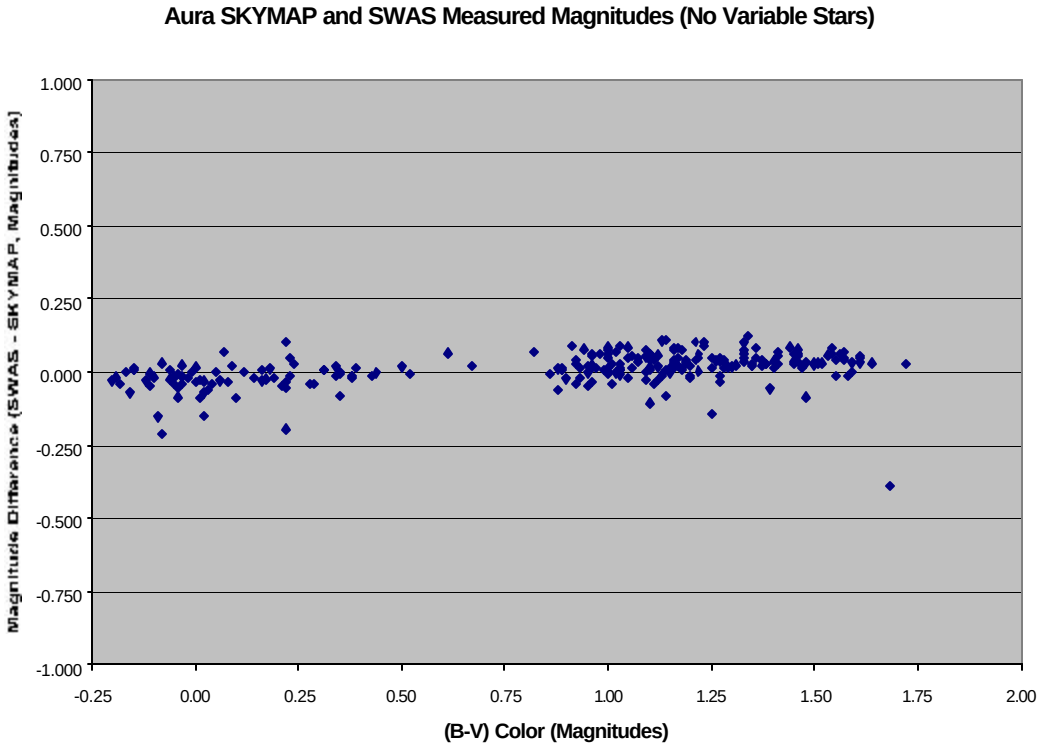


**Figure A-6. Aura SKYMAP and SWAS Measured Magnitudes**